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Targeted Oxygen Addition to Hood Canal: A Potential Management Strategy to Ameliorate the Impacts of Hypoxia

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Keywords: Hood Canal, Hypoxia, Eutrophication, Oxygenation

Abstract

Hood Canal is a 60-mile-long fjord located on the western side of Puget Sound. The fjord is up to 500 feet deep and has limited water exchange with Puget Sound because of a shallow sill at its mouth. Bottom waters in Hood Canal commonly exhibit hypoxia (DO < 2-3 mg/L), and hypoxia is the likely cause of recent fish kills observed in the canal. The severity of hypoxia, particularly in the southern end of the canal, appears to have increased over the past decade. Oxygen levels measured in Lynch Cove in December 2003 (~0.5 mg/L) were the lowest on record for the site. Hypoxia may be the result of cultural eutrophication, with septic tanks being the largest external source of nitrogen to the water body (39-241 tons/year). Aeration using pure oxygen gas is a relatively new management strategy to improve DO levels in water bodies. The strategy has been used to economically oxygenate a number of water bodies ranging from small lakes (Newman Lake, Washington) to discharges from enormous reservoirs (Douglas Reservoir, Tennessee). This paper will discuss oxygenation technology and review a number of case studies. It will also present a preliminary evaluation of the potential to oxygenate portions of the Hood Canal. The primary advantage of oxygenation is that it would immediately alleviate the impacts of hypoxia in areas where oxygen was delivered. Initial estimates show that targeted oxygen addition of 5 tons per day to the southern end of the canal would cost on the order of $1,000 per day and treat roughly one mile of canal.

Introduction

Hood Canal is located on the western side of Puget Sound. The canal is 60-mile-long, up to 500 feet deep, and ranges from one-half to four miles wide. The far end of the canal includes the mouth of the Skokomish River, the dominant freshwater inflow. The canal is a typical fjordal system in which freshwater from rivers override cold saline marine waters. A glacially generated sill near the inlet in the vicinity of South Point impedes water exchange between the canal and the waters of Admiralty Inlet and beyond. Based on the 2000 census data, roughly 54,000 people live in the Hood Canal watershed (PSAT 2004). The canal experiences low dissolved oxygen (DO) events, particularly in the Great Bend area between Potlatch State Park and Hoodsport. Bottom waters in Hood Canal commonly exhibit DO levels below 2 to 3 mg/L (Newton et al. 2004). A number of hypoxia events have been documented in which aquatic biota have been severely stressed or killed (Palsson et al. 2005). The severity of hypoxia, particularly in the southern end of the canal, appears to have increased over the past decade. For example, oxygen levels measured in Lynch Cove in December 2003 (~0.5 mg/L) were the lowest on record for the site (Newton et al. 2004).

A number of complex factors may contribute to the hypoxia problem in the canal including climatic changes, modifications in freshwater inputs, and variations in basin mixing processes (Newton 2005). Cultural eutrophication is likely a primary factor in the worsening DO conditions in the canal. In a comprehensive preliminary evaluation of nitrogen sources to the canal, the Puget Sound Action Team (2004) estimated that septic tank loading was the largest external source of nitrogen to the water body (39-241 tons per year). Other significant sources of nitrogen include stormwater runoff (12-24 tons per year), salmon carcass disposal (16-24 tons per year), and agriculture/animal waste (18-22 tons per year). Nitrogen is generally the limiting nutrient in coastal waters, and its input to the canal likely results in increased algal productivity in the surface waters. When the algae die, they sink into the deep waters of the canal where they are biodegraded by bacteria that utilize dissolved oxygen in the process. This, in combination with the relative isolation of canal bottom waters, helps to exacerbate low oxygen conditions in the canal bottom waters. Additional potential oxygen sinks in bottom waters include respiration by aquatic biota as well as the addition of organic wastes from human activities (e.g., boats and fish processing). Under severe hypoxic conditions, aquatic organisms will flee if they are mobile or perish.

Figure 1 shows typical water quality in the Great Bend area, immediately South of Sisters Point (Station HCB004), during the summer low river flow season (Washington Department of Ecology 2005). The figure includes water quality profiles for temperature, DO, salinity, and sigma-t (a measure of density) for Station HCB004 for July 23, 2002. The canal waters are stratified as a result of both solar heating of surface waters and freshwater input, with

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the surface layer encompassing the upper seven meters of the water column. DO levels in the upper surface layer, which are exposed to DO replenishment from both the atmosphere and from algal activity, are around 8 mg/L. At around seven meters DO exhibits a pronounced metalimnetic oxygen maximum. Such maxima are commonly the result of oxygen produced by algae that become trapped atop the pycnocline, the point of maximum density gradient (Horne 1994). Below the pycnocline, where waters have no source of reoxygenation, DO levels rapidly drop with depth and anoxic conditions (no oxygen) are predominant below 22 meters.

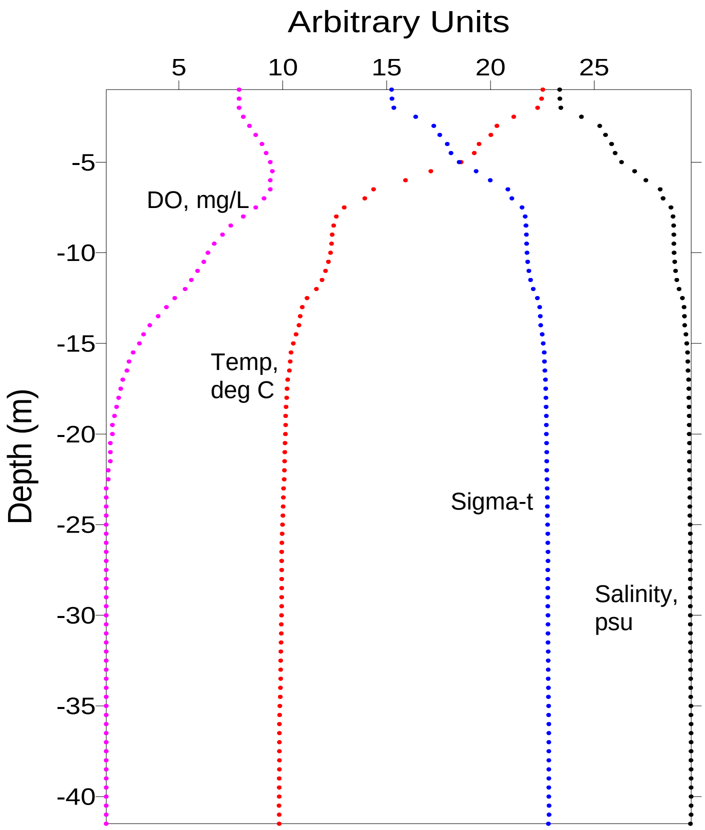

Figure 1. Water Quality in the Great Bend Station WDOE HCB004, July 23, 2002.

Oxygenation Technology and Systems

Oxygenation is a relatively new aeration technique used to prevent anoxia in lakes and rivers (Beutel and Horne 1999). Oxygenation systems generally consist of a liquid oxygen storage facility onshore. Evaporators transform the liquid oxygen to gas, and the gas is dissolved into the receiving water through an onshore contact chamber, a system of diffusers located under water, or a contact chamber submerged in the lake. Alternatively, oxygen gas can also be manufactured onshore for immediate use with a vacuum pressure swing adsorption system which includes a system of air blowers, oxygen gas adsorbent vessels, an oxygen surge tank, and various valves and computer controls. The use of pure oxygen gas over air as a source of oxygen has a number of advantages. In deep waters, high rates of oxygen gas can be injected while still preserving thermal stratification, thereby improving habitat for cold-water aquatic biota. As a result of high solubility and transfer efficiencies, the size of the mechanical devices and recirculation rates needed using pure oxygen are fairly modest. High oxygen delivery rates allow for the maintenance of high levels of DO in bottom waters throughout the stratified period (Thomas et al. 1994, Horne 1995, Prepas and Burke 1997). Additional advantages of oxygenation include avoidance of hypolimnetic dissolved nitrogen supersaturation (Fast et al. 1975), low energy use (Speece 1994), and low commercial oxygen costs of

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around $100 per ton (personal communication, Air Liquide, February 2005). Three main types of oxygenation systems are currently in use including bubble plume, linear diffuser, and submerged contact chamber oxygenation. The underwater components of these three systems are shown in Figure 2 and summarized in the text below.

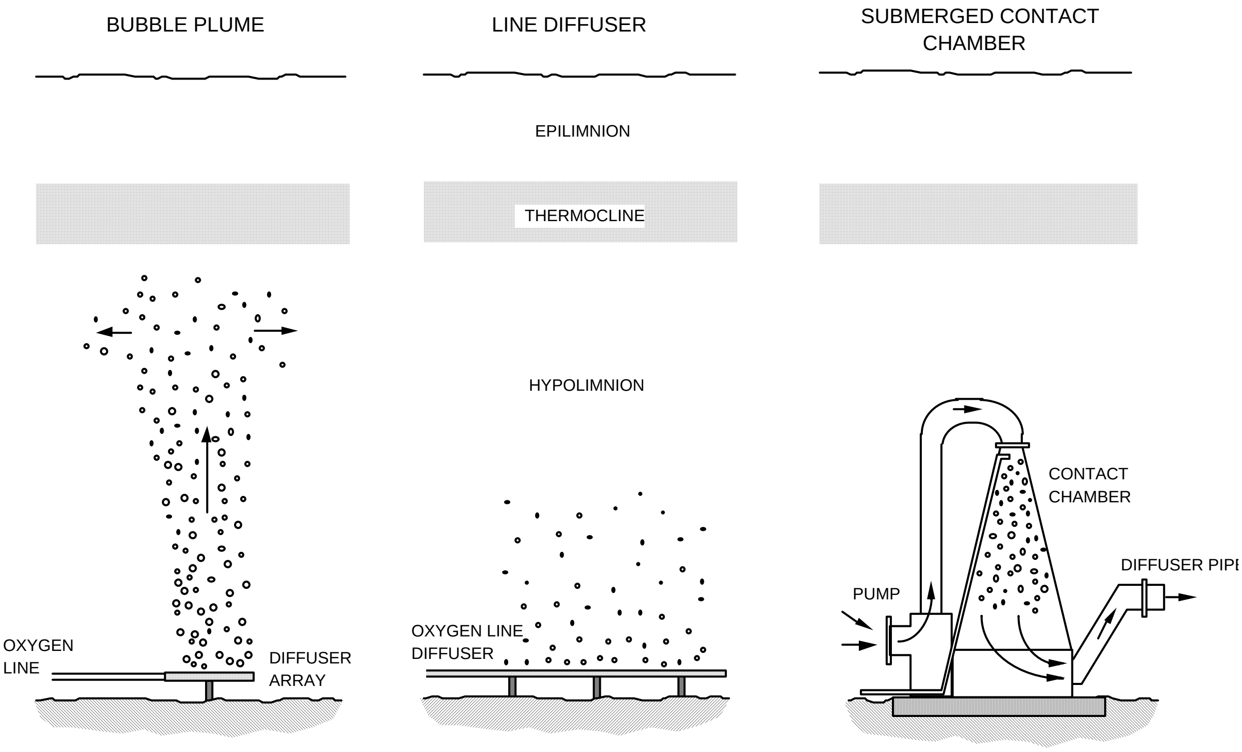

Figure 2. Schematics of Three Primary Methods of Oxygenation.

Bubble Plume Oxygenation

Bubble plume oxygenation works by injecting pure oxygen through a dense group of diffusers at the lake bottom. Oxygen bubbles dissolve into a surrounding plume of rising water. The oxygenated plume then detrains and spreads out horizontally below the thermocline. The technology was developed in Switzerland in the early 1980s to inhibit high rates of internal phosphorus loading in deep, eutrophic lakes (Imboden 1985, Gächter and Wehrli 1998). In Lake Baldegg (137,900 acre-ft), the system consists of an oxygen tank and an air compressor onshore connected to six diffuser arrays located near the bottom of the lake. Artificial mixing via compressed air is maintained from November through May by injecting 6 metric tons per day (t/d) of air through 3-4 deep diffusers. Hypolimnetic oxygenation is operated from May through November with 3-4 t/d of oxygen injected through 4-6 diffusers. Phosphorus release is still observed during the summer, but oxygenation did cause a decrease in hypolimnetic accumulation of ammonia and manganese (Gächter and Wehrli 1998). In some lakes, the system appears to have trouble maintaining a well oxygenated sediment water interface because most of the oxygen is distributed to the upper levels of the hypolimnion (McGinnis, personal correspondence).

Linear Diffusers

Linear diffuser oxygenation systems consist of an extensive network of linear diffusers that release fine oxygen bubbles that rapidly dissolve into the overlaying water column. In the early 1970s, the Tennessee Valley Authority (TVA) began examining the feasibility of oxygenation for reaeration of hydroelectric reservoir discharges with low DO at Fort Patrick Henry Dam, Tennessee (Nicholas and Ruane 1975). Since then, the TVA has installed diffuse deep-water oxygenation systems in over half a dozen reservoirs ranging in volume from 200,000 to 1.5 million acre-

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feet. Delivery rates of the system range from 15 to 150 t/d. The linear diffuser system has a few advantages over other systems. In contrast to contact chambers, the system does not require the pumping of water. In addition, unlike the bubble-plume oxygenation system, at low gas flow rates the system does not induce large-scale vertical current of water. Thus, dissolved oxygen tends to stay deeper in the reservoir. A system now in operation at Douglas Dam, Tennessee (1.4 million acre-ft) has successfully oxygenated large turbine discharges since 1993 (Mobley and Brock 1995). The reservoir is a large power generation reservoir located on the French Broad River. During the late summer, turbine releases from Douglas Dam historically contained low DO and noxious levels of hydrogen sulfide. The system has 16 diffuser lines that include 1,200 m each of porous hose. The hose is fed pure oxygen from an onshore facility that includes a large capacity liquid oxygen storage tank and multiple evaporator units.

Submerged Contact Chambers

The submerged contact chamber oxygenation systems consist of a submerged cone-shaped contact chamber mounted on the lake bottom. A submersible pump draws water from the hypolimnion into the top of the cone. Oxygen supplied from an onshore facility is injected at the top of the cone. The oxygenated water is discharged through a horizontal diffuser pipe. In an experimental bench-scale chamber, Speece et al. (1971) observed oxygen transfer efficiency in the range of 80-90%. With the proper horizontal dispersion of reoxygenated water, a submerged chamber system can overcome potential limitations of a bubble plume or diffuse deep-water system. These include accidental destratification caused by oxygen bubbles rising through the thermocline (Speece 1994) and localized anoxia as a result of limited oxygen dispersion within the hypolimnion (Fast and Lorenzen 1976). In addition, in contrast to bubble plume and diffuse deep-water systems, horizontal dispersion sends reoxygenated water out over the sediments of the reservoir, thereby keeping highly oxygenated water in direct contact with the sediments and assuring a well-oxygenated sediment-water interface.

Submerged contact chamber systems have been successfully operated in two lakes in the Western US to improve fish habitat. Newman Lake (23,000 acre-ft) is located 15 miles east of Spokane in eastern Washington. The lake is an important recreational resource, but low oxygen levels in bottom waters during the summer resulted in a severely degraded cold-water fishery. A 1.5 t/d contact chamber oxygenation system has been in operation since 1992 and has dramatically improved bottom water quality for fish during the summer by maintaining a well-oxygenated hypolimnion (Doke et al. 1995, Moore et al. 1996). Camanche Reservoir (417,100 acre-ft) is a large, multi-purpose reservoir located in the foothills of the Sierra Nevada Mountains in Northern California. A fish hatchery just downstream of the reservoir experienced a large fish kill in the late 1980s due to hypoxic conditions. A 8 t/d contact chamber oxygenation system was installed in 1993, and no fish kills have occurred since its operation began. Spatial monitoring of DO in 1993 to 1994 showed that a well-oxygenated plume of deep-water migrated up the reservoir about 3 km after 40 days after oxygenation (Speece 1994, Horne 1995).

Targeted Oxygenation Addition to Hood Canal

Oxygenation using pure oxygen gas is a proven technology that has been implemented on a large scale, and has a history of successful operation. This technology may be applicable to ameliorating hypoxic conditions in Hood Canal. However, oxygenation is not a “silver bullet” and should be considered as complementing the ongoing scientific study of the ecosystem and implementation of various source control strategies. Due to the enormous area and volume of the canal, it is not economically feasible to oxygenate its entirety. Instead, the concept of targeted oxygenation should be considered. Targeted oxygenation includes three components: one ecologically oriented, the second engineering based, and the third hydrodynamic related. The first component is the identification of areas in the canal that provide critical ecological function and value. These may be areas of high shellfish production, critical refuge for specific fisheries, or already identified resources such the Sund’s Rock Marine Reserve. The second component includes the injection of oxygen gas near the critical resource area using an appropriate engineered system. As discussed in more detail below, the most appropriate system for the canal is a barge-based or bottom-mounted linear diffuser system. Additional design and operating concerns regarding oxygenation in a marine environment include corrosion and biofouling.

The third component of targeted oxygenation is the use of natural advection and dispersion to deliver and spread the oxygen to and throughout the critical resource areas. As noted earlier, natural currents dispersed oxygen injected into Camanche Reservoir up the reservoir about 3 km after 40 days of oxygenation. Currents in the canal should help to disperse injected oxygen, however currents vary both spatially and temporally. For example, bottom water currents east of the great bend reportedly range from 0 to 5 cm/sec and current direction oscillates from east to west on roughly a 12 hour cycle (Cannon 2005). By coupling a knowledge of canal ecology (critical resource area), engineering (oxygenation system design and implementation), and canal hydrodynamics (spatial and temporal patterns of local mixing), a properly engineered system has a high likelihood of ameliorating problems associated with hypoxia in limited areas of ecological significance within the canal.

Recommended System For Hood Canal

Based on an evaluation of oxygenation technologies, we recommend pursing two potential systems for pilot scale testing: land-based liquid oxygen (LOX) storage with submerged linear diffuser and barge-based LOX storage with barge-deployed diffuser. The bubble plume system is not recommended since it imparts a significant vertical momentum into the water column, and if not operated within specific constraints could result in mixing of nutrient-rich bottom waters upwards into the photic zone. This could exacerbate algal growth and subsequent exertion of oxygen demand in bottom waters. A submerged contact system is not recommended since is requires substantial underwater facilities including a submerged pump and multiport diffuser. The cost of electrical cable to the chamber could be cost prohibitive and the underwater infrastructure would be vulnerable to corrosion and biofouling. Advantages of a linear diffuser system include low potential for vertical mixing, no moving parts, and the relative low cost of diffuser line (~$50 per foot). In addition, the diffuser line can be easily brought to the surface by filling a buoyancy line with air. A detailed schematic of the linear diffuser system is shown below in Figure 3.

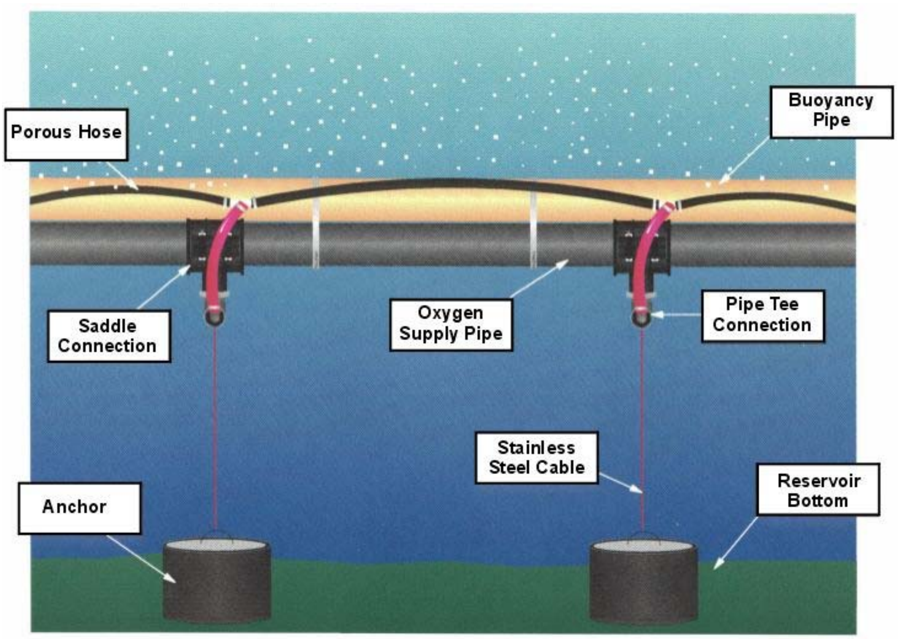

Figure 3. Schematic of Linear Diffuser System.
(Complements of Mark Mobley, Mobley Engineering)

Rather than mounting the linear diffuser on the bottom of the canal, it could be deployed from a barge. A barge system has a number of potential advantages over a permanent installation of a linear diffuser. The main advantage is that the depth and lateral position of oxygen injection could be varied daily, or even hourly. In addition, the diffuser array could be stored above water during non-use, thereby limiting biofouling of the diffusers and facilitating regular maintenance.

The primary design parameter to size an oxygenation system is the biological oxygen demand in the deep water of the canal. A rough estimation of oxygen demand was made using the difference in bottom water DO concentrations at two water quality stations in Hood Canal, the distance in miles between those stations, and an assumed southerly velocity of 2.5 centimeters per second for the deep water. An additional estimate of the oxygen demand was made by examining the rate of oxygen decline in the early summer at specific sites in the canal. The oxygen demand in canal bottom water is roughly 0.05 to 0.1 mg O_2/L/day. This is comparable to typical values observed in mesotrophic lakes (Beutel 2003). Based on this consumption rate, a volume of canal bottom water on the order of 1 mile long, 1 mile wide, and 60 feet deep would require roughly 5 t/d of oxygen, presuming that the oxygen could be evenly distributed throughout the volume. This is a relatively modest oxygenation system and is comparable to those installed at a number of sites (e.g., Newman Lake, Washington, 1.5 t/d; Upper San Leandro Reservoir, California, 5 t/d; Camanche Reservoir, California, 8 t/d). It is far smaller than the 100 t/d systems implemented to oxygenate releases from large hydroelectric impoundments in the southern US.

Preliminary System Costs

Costs associated with a land-based linear diffuser system include an onshore LOX storage unit and evaporators, and diffuser line running from the onshore facilities to the bottom of the canal. A rough estimate of capital costs associated with a permanent 5 ton per day pilot system is included in the Table 1, and totals $400,000. Operating costs would include oxygen use at roughly $500 per day or $75,000 assuming 150 days of operation, as well as annual maintenance estimated at $25,000 per year, for a total annual operating cost of $100,000. Annualizing the capital costs, adding the operating cost, and spreading the total annual cost over a 150 day operational duration yields a unit cost of around $1,000 per day for the 5 t/d pilot system. Note that a smaller, more temporary pilot system could be tested with a corresponding drop in costs mainly associated with onshore facilities and oxygen use, however it would have less of a “signal” in the canal. In addition, some components such as the onshore facilities could be rented for a short duration, thereby decreasing the cost of a short-term pilot study. Cost for a barge-based diffuser system is anticipated to also be in the range of $1,000 per day, with costs for onshore facilities replaced with costs associated with barge purchase and operation.

Table 1. Estimated Capital Cost of 5 ton per day Oxygenation Pilot System for Hood Canal.

Component	Rough Cost Estimate
10,000 gallon (~50 tons) LOX storage tank & evaporators	$100,000
Miscellaneous site work	$50,000
2,000 feet of supply line (from onshore facilities to diffuser)	$70,000
2,000 feet of linear diffuser	$100,000
~25 percent Contingency	$80,000
System Capital Cost	$400,000

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